Influence of irrigation time and frequency on greenhouse gas emissions in a solid-set sprinkler-irrigated maize under Mediterranean conditions

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Abstract

Irrigation management may influence soil greenhouse gas emissions (GHG). Solid-set sprinkler irrigation systems allow to modify the irrigation time and frequency. The objective of this study was to quantify the effect of two irrigation times (daytime, D; nighttime, N) and two irrigation frequencies (low, L; high, H) on soil carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions in a solid-set sprinkler-irrigated maize (*Zea mays* L.) field located in NE Spain during 2015 and 2016 growing seasons and the fallow period between growing seasons. Compared with D irrigation, N irrigation increased soil water content (0-5 cm) in both growing seasons. Irrigation management did not affect CH_4 emissions and the soil acted as a sink of CH_4. Cumulative CO_2 emissions were affected by the measurement period (growing season vs fallow) with the greatest values in 2015 growing season, being 81 and 32 % higher over the fallow period and over the 2016 growing season, respectively, due to the effect of the preceding crop, alfalfa, and a better soil moisture conditions for the microorganism activity. Similarly, cumulative N_2O emissions showed the highest values in 2015, reporting values 90 and 51% greater than the fallow period and the 2016 growing season, respectively. Moreover, N irrigation increased cumulative N_2O emissions by 29 % compared with D irrigation, but irrigation frequency did not affect cumulative N_2O emissions. Irrigation time did not affect cumulative N_2O emissions scaled per grain yield or per N uptake because N irrigation increased maize yield by 11% compared with D irrigation. Due to the lack of differences in the scaled N_2O emissions, N irrigation should be consider as an appropriate strategy to optimize grain yield without compromising soil GHG emissions per unit of grain yield in Mediterranean agroecosystems.

Keywords:

Soil N_2O emissions, Sprinkler irrigation management, maize monoculture, yield scaled N_2O emissions

Abbreviations

CIR, crop irrigation requirement; ETo, reference evapotranspiration; ETc, crop evapotranspiration; GMT, greenwich mean time; WFPS, water-filled pore space.

1. Introduction

Agricultural practices have an important role in GHG emissions (Smith et al., 2008). According to the latest National GHG Inventory, agriculture is responsible of about 11 % of the total GHG emissions in Spain. Soils are the principal source of non-CO_2 agricultural emissions (MAPAMA, 2018).

It is well established that soil water content is a major factor in soil GHG emissions. Soil CH_4 production and consumption is controlled by many different factors, such as soil water content, pH and redox potential among the most important (Wang et al., 1993). Le Mer and Roger (2001) described methanogenesis as a biological process that requires strict anaerobiosis and low oxidation-reduction potentials. For example, in a Mediterranean rice paddy experiment, a midseason drainage favoured the oxidation conditions in the soil and thus the decrease of CH_4 emissions (Meijide et al., 2017). Moreover, Wang et al. (2016) observed an increment in the CH_4 net uptake when surface drip irrigation was compared with flood irrigation systems due to the lower soil moisture in drip irrigation systems. Soil microorganisms through the nitrification and denitrification processes (Firestone and Davidson, 1989; Bremner, 1997) control N_2O production in the soil. Nitrification is the main process contributing to N_2O production under aerobic conditions, when the water-filled pore space (WFPS) is below 60%. However, when WFPS is above this threshold (60 % WFPS), denitrification is the predominant process involved in N_2O production (Linn and Doran, 1984; Davidson et al., 2000; Bateman and Baggs, 2005). Moreover, CO_2 emissions from soils are a consequence of root respiration and microbial decomposition of organic matter and are regulated by soil temperature and soil water content (Davidson and Janssens, 2006). Thus, the increase of soil moisture content due to irrigation water applied can result in more optimal conditions for soil microorganism activity, and thus resulting in an increase of CO_2 emissions from the soil (Linn and Doran, 1984).

Irrigation systems, due to their capacity to modify the soil water content may have an important role in soil GHG emissions, especially under Mediterranean conditions where irrigation is a common practice (Aguilera et al., 2013; Sanz-Cobena et al., 2017).

Sprinkler irrigation systems are widely used around the world and increasingly adopted in many irrigated areas of Spain due to several reasons: the higher crop yields provided compared with traditional surface irrigation systems (Lecina et al., 2010), because they allow applying small amounts of irrigation water so runoff and drainage are minimized, and because they allow automation, thus reducing labour requirement and costs for farmers (Playán and Mateos, 2006). Although center pivots are mainly used as sprinkler system around the world, the solid-set sprinkler system is mainly used in many areas of Spain.

Solid-set systems are more flexible than center pivots for irrigation management, allowing easily to choose the irrigation time (day or night) and frequency. These irrigation management factors affect soil water content and crop yields (Urrego-Pereira et al., 2013; Cavero et al., 2016; Cavero et al., 2018). Thus, soil water content decreases with daytime sprinkler irrigation due to the higher water evaporation losses (Urrego-Pereira et al., 2013; Cavero et al., 2016). Besides, increasing irrigation frequency decreased soil water content when sprinkler irrigation was performed during daytime (Cavero et al., 2018).

In the river Ebro valley of Spain maize is one of the main irrigated crops under sprinkler irrigation. In this area, solid-set sprinkler irrigation is scheduled at one to five days intervals, 08:00h and 20:00h being the most used irrigation starting times (Salvador et al., 2011a). In the last decade, several experiments have been carried in this area to evaluate the efficiency of sprinkler irrigation on crop water requirements and crop performance (Cavero et al., 2003; Dechmi et al., 2003; Salvador et al., 2011b). These studies identified irrigation scheduling as an important factor in crop production. Recently, other investigations have determined the impact of nitrogen fertilization management on soil greenhouse gas (GHG) emissions in sprinkler-irrigated maize (Álvaro-Fuentes et al., 2016; Maris et al., 2018). However, to date there is no information about the influence of sprinkler irrigation management and, particularly, the effect of sprinkler irrigation time and frequency on GHG emissions in Mediterranean soils.

Hence, this study was aimed to evaluate the impact of the irrigation time (daytime or nighttime) and frequency (low and high) on soil GHG emissions in a maize crop irrigated with of a solid-set sprinkler system.

2. Material and Methods

2.1 Site description and experimental design

The field experiment was carried out during 2015 and 2016 in a 2.34 ha maize field irrigated with a solid-set sprinkler system, located at the experimental farm of the Aula Dei Experimental Station, Zaragoza, Spain (41º 43´ N, 0º 48´ W, 225 masl). The climate is Mediterranean semiarid with annual mean air temperature of 14.1 ºC, annual precipitation of 298 mm and grass reference crop evapotranspiration (ETo) of 1243 mm. The soil is a clay loam classified as Typic Xerofluvent (Soil Survey Staff, 2014). Specific properties of the experimental soil are detailed in Table 1.

2.2 Experimental design

A field experiment under sprinkler irrigation was established in 2015 to compare the effect of the irrigation time and the irrigation frequency on a maize (*Zea mays* L.) monoculture. Prior to the establishment of the field experiment, alfalfa cv. Aragón (*Medicago sativa* L.) was grown during three years (2012-2014).

The experimental field was divided in twelve irrigation sectors, which were irrigated independently by four sprinklers. The sprinkler spacing was a square of 18 m × 18 m. Sprinkler application rate was 5 mm h^{-1} and the wetted radius was 15 m.

Tillage operations consisted of one pass of a subsoiler to 30 cm depth followed by one pass of a disk harrow and one pass of a rotary tiller just before planting. All tillage operations were made with commercial tillage equipment (Table 2). Maize cv. Pioneer P1785 was planted on April in rows 75 cm apart at a planting density of 89,500 plants ha^{-1} (Table 2). Fertilization consisted of 64 kg ha^{-1} N, 120 kg ha^{-1} P_2O_5, and 120 kg ha^{-1} K_2O applied before sowing, and 100 kg ha^{-1} N of N-32 (8 % ammonium N ($N\text{-}NH_4$) - 8 % nitrate N ($N\text{-}NO_3$) - 16% amide N ($N\text{-}NH_2$)) solution applied with the irrigation water in two growth stages (at V6 and V12) as top dressing application. In 2015 only one top dressing of N (100 kg ha^{-1} N) was applied with the irrigation water at V6 because of the carryover N effect of the previous alfalfa crop (Tabla 2). Fertigation with N-32 solution was done in one irrigation lasting 2 hours followed by an additional one-hour irrigation to wash out the nitrogen fertilizer from the maize plants and incorporate it into the soil. Harvest was carried out with a commercial combine (Table 2). The maize stover was chopped and spread over the soil by the same machine. Weed and pest control was done according to best management practices in the area.

Maize evapotranspiration (ETc) was calculated using ETo and crop coefficient (Kc) values (Allen et al., 1998). Meteorological data from a weather station located 1 km southwest from the field experiment were used to compute ETo using the FAO Penman-Monteith method (Allen et al., 1998). Crop coefficients (Kc) were calculated as a function of thermal time using an equation developed by Martínez-Cob (2008) at the same location of the experiment. Thermal time was computed as the cumulative daily difference between daily mean air temperature and a basal air temperature of 8 °C (Kiniry, 1991). Daily crop evapotranspiration of maize (ETc) was then obtained as ETo multiplied by Kc. The crop irrigation requirements (CIR) were determined weekly as the difference between the ETc and the effective precipitation, which was estimated as 75% of total weekly precipitation (Dastane, 1978). The irrigation amount applied to the crop was equal to the CIR (Table 3). Irrigation was applied at nighttime to all the experimental plots until the crop was well established (V6 to V8 growth stage) in order to have the same plant density and because limitations for irrigation scheduling at nighttime are generally not relevant during the period of lower CIR.

The experimental layout was a randomized factorial design with two factors (with two levels each) and three replicates per treatment, so twelve plots were used. The plot size was 18 m x 18 m, coinciding with that of the irrigation sector. The two factors tested were irrigation time of the day and irrigation frequency. For irrigation time the levels were daytime (D) or nighttime (N). For irrigation frequency the levels were: two irrigation events per week on Monday and Thursday (low frequency, L) or daily irrigation (high frequency, H). Therefore, four different treatments were tested: daytime low frequency, DL; daytime high frequency, DH; nighttime low frequency, NL, and nighttime high frequency, NH. The same amount of irrigation water was applied to all the treatments and was calculated weekly, as explained. The starting time for irrigation was generally 1000 h Greenwich Mean Time (GMT) for daytime irrigations and 2200 h GMT for nighttime irrigations. The irrigation duration of the high frequency treatment was at least 1 h, so if the weekly CIR was lower than 7 h, irrigation was not applied daily.

2.3 Gas sampling and analyses

Gas sampling began in April 2015 and extended until September 2016 using the closed chamber technique (Hutchinson and Moiser, 1981). Soil greenhouse gases (CO_2, CH_4 and N_2O) were measured weekly from planting until mid-August (tasseling stage, VT growth stage), every two weeks from mid-August until harvest and every three weeks during the fallow period (November-March). Gas sampling frequency was increased during tillage, planting and fertilization operations. For tillage operations, soil gas samples were taken 24 h before and 24 and 96 h after tillage operations. In the case of planting and fertilization operations, soil gas samples were taken 24 h before and 24, 48, 72, 96, 144 and 192 h after each operation. In 2015, gas sampling was performed every Tuesday, after all the four different treatments were irrigated during the day and the night before, so less than 24 h passed between the irrigation and the gas sampling. However, in 2016, in order to maximize the effect of the irrigation frequency, gas sampling was performed every Thursday, that is less than 24 h passed between the irrigation and the gas sampling for the high irrigation frequency treatments, but more than 48 h for the low irrigation frequency treatments.

At the beginning of the field experiment, two polyvinyl chloride (PVC) rings (31.5 cm internal diameter) per plot were inserted 5 cm into the soil. The rings were only removed at tillage, planting and harvesting operations. PVC chambers (20 cm height) were fitted into the rings before gas sampling. A polytetrafluoroethylene vent (10 cm long and 0.4 cm internal diameter) was installed on one side of the chambers to prevent possible changes in pressure during the deployment of chambers and gas sampling (Plaza-Bonilla et al., 2014). In order to diminish internal increases in temperature the chambers were covered with a thermal reflective insulation fabric (AislaTermic®, Arelux, Cuarte de Huerva, Zaragoza, Spain) that consisted of two reflective layers of aluminium film bonded to an inner layer of polyethylene bubbles. A metal fitting was attached in the center of the top of the chamber and lined with two silicone-FEP (Tetrafluoroethylene-hexafluoropropylene) septa as a sampling port.

Gas samples were collected at 0, 20 and 40 min after chamber closure using a 20-mL polypropylene syringe (Becton-Dickson, Plastipak ™) with a 25 mm-long needle (Becton-Dickson, Microlance™), and 20 mL of gas sample was transferred to an evacuated 12-mL Exetainer® borosilicate glass vial (model 038W, Labco, High Wycombe, UK). The air temperature inside the chamber was measured introducing a thermometer in the chamber before closing the chambers.

Concentrations of CO_2, CH_4 and N_2O were measured in the gas samples with an Agilent 7890B gas chromatograph equipped with a flame ionization detector (FID) for CO_2 and CH_4 and an electron capture detector (ECD) for N_2O. A previous stage is necessary to determine the CO_2 concentration in the gas samples, consisting in passing the gas samples through a methanizer before entry into the FID detector. Gas samples were injected automatically using a PAL3 autosampler. A HP-Plot Q column (15 m long, 320 μm in section and 20 μm thick) was used, with helium as a carrier gas at 2 mL min^{-1}. The injector and the oven temperatures were set to 50 and 35ºC, respectively. The temperatures of the FID, the methanizer and the ECD were set to 250, 375 and 280ºC, respectively. For the FID, helium was used as a make-up gas at 25 mL min^{-1} and a 5% methane in argon gas mixture at 30 mL min^{-1} was used as a make-up gas for the ECD. The volume of sample injected was 1 mL. The system was calibrated using ultra-high purity CO_2, CH_4 and N_2O standards (Carburos Metálicos, Barcelona, Spain).

Emission rates were calculated taking into account the linear increase in the gas concentration within the chamber during the sampling time and correcting for the air temperature inside the chamber.

2.4 Soil, biomass and grain yield sampling and analyses

Soil samples from the 0–5 cm soil layer were collected on each sampling date close to every gas sampling chamber to quantify the ammonium (NH_4^+) and nitrate (NO_3^-) ions content in the soil. Besides, soil temperature and water content were measured using a Crison TM 65 probe (Carpi, Italy) and GS3 soil probes (Decagon Devices, Pullman, WA), respectively. Soil NH_4^+ and NO_3^- contents were obtained by extracting 50 g of fresh soil with 100 mL of 1 M KCl. The extracts were frozen and afterwards analysed with a continuous flow autoanalizer (Seal Autoanalyzer 3, Seal Analytical, Norderstedt, Germany). Both ions were transformed to kg N ha^{-1} taking into account soil moisture and bulk density. Soil bulk density was determined using the cylinder method (Grossman and Reinsch, 2002). The WFPS (%) was calculated from the volumetric soil moisture content and soil bulk density measurements, assuming a soil particle density of 2.65 Mg m^{-3}

Maize aboveground biomass and grain yield were determined manually before the machine harvest by cutting the plants at the soil surface level on 3 m along the planting row at two randomly selected locations per plot. The number of plants and ears was counted. The grain was separated from the cob and both parts were dried at 60 ºC for 48 h and weighed. Besides, a sub-sample of four entire plants was taken, oven-dried at 60 °C for 48 h and weighed. Afterwards the plant and grain subsamples were grounded and analyzed to determine the C and N content by combustion (TruSpec CN, LECO, St Joseph, MI, USA). The rest of maize plants at each experimental plot was harvested with a commercial combine. Maize grain moisture was determined and grain yield was standardized to 14 % moisture content.

2.5 Data analysis

Cumulative soil C and N emissions due to the fluxes of CO_2, CH_4 and N_2O during the whole experimental period were quantified on a mass basis (i.e., kg C ha^{-1} and kg N ha^{-1}) using the trapezoid rule. This involves linear interpolation between the data points, calculating the area of each trapezoid formed and summing these areas to give the cumulative emissions (Levy et al., 2017). Sqrt-transformations were done for CO_2 fluxes and WFPS values, and a logarithm transformation was done for N_2O fluxes. Transformed data for CO_2 and N_2O fluxes, and WFPS and soil NH_4^+ and NO_3^- content, and soil temperature were analyzed using the JMP 10 statistical package (SAS Institute Inc, 2012) performing a repeated measures analysis of variance (ANOVA) with irrigation time, irrigation frequency, date of sampling and their interactions as sources of variation for each measurement period (i.e. 2015, 2015 growing season; fallow, fallow period; 2016, 2016 growing season). In addition, different ANOVA were performed for cumulative C and N emissions, grain yield, grain yield-scaled N_2O emissions ratio and grain N-uptake scaled N_2O emissions ratio with irrigation time, irrigation frequency, measurement period and their interactions as sources of variation. Previous to the ANOVA analysis, logarithm transformations were done for cumulative N_2O emissions, grain yield-scaled N_2O

emissions ratio and grain N-uptake scaled N_2O emissions. When significant, differences between treatments were identified at 0.05 probability level of significance using a Tukey test. The relationships between the fluxes of CO_2, CH_4 and N_2O and the soil NH_4^+ and NO_3^- content, the WFPS and the soil temperature were analysed by simple regressions with the JMP 10 statistical package (SAS Institute Inc., 2012).

3. Results

3.1 Environmental conditions, WFPS and soil ammonium and nitrate content.

Daily precipitation, mean daily air temperature and daily reference evapotranspiration, ETo, for the 2015 and 2016 growing seasons are shown in Figure 1.

A large variation in temperature and precipitation were recorded during the two growing seasons as expected in Mediterranean conditions. Air temperature showed the highest values during the summer months (June-August) and the lowest during the winter months (December-February).

The sampling date was significant for the most part of the variables considered in this work (Table 4). Moreover, for some of these variables the interaction between sampling date and irrigation time and frequency was also significant. Table 4 only shows the results of irrigation time, irrigation frequency and their interaction. However, when the interaction between irrigation time, irrigation frequency and sampling date was significant, the results are presented graphically.

The WFPS was affected differently depending on the measurement period (i.e. 2015 growing season, fallow, 2016 growing season) (Table 4, Figure 2). The WFPS was affected by the irrigation time and frequency during the 2016 growing season (2016 hereafter) maize season, while it was affected by the interaction of both variables in 2015 growing season (2015 hereafter). In both growing seasons, the nighttime irrigation showed greater WFPS compared to the daytime irrigation. Besides, in 2016 high frequency irrigation showed greater WFPS compared to low frequency irrigation. However, in 2015, the high irrigation frequency only increased the WFPS when irrigation was applied at night. As expected, the WFPS during the fallow period was not affected by the irrigation management, because irrigation water was not added during this period.

Soil NO_3^- and NH_4^+ contents were significantly affected by the sampling date (Table 4). Moreover, in 2015, soil NH_4^+ content showed a significant interaction between irrigation time and sampling date. In this period, the highest value of soil NH_4^+ was observed under D irrigation during the week after the top dressing application of the nitrogen fertilizer.

3.2 Soil CO_2, CH_4 and N_2O fluxes.

Soil CO_2 emissions were affected by irrigation time, irrigation frequency and sampling date in 2015 and 2016, but not during the fallow period (Table 4, Figure 3). During both growing seasons, soil CO_2 fluxes showed a similar behaviour with an increase in the emission rates along the maize crop growth reaching the maximum values in July coinciding with maize tasseling stage (VT). Moreover, in 2015, mean CO_2 flux values ranged between 2.34 to 2.06 g CO_2-C m^{-2} day^{-1}, while in 2016 the mean CO_2 flux values varied from 1.74 to 1.48 g CO_2-C m^{-2} day^{-1} involving a reduction of 27% in the CO_2 flux mean in 2016 compared with 2015. After this maximum emission value, soil CO_2 fluxes decreased reaching the minimum values during the fallow period, with mean CO_2 flux values lower than 0.5 g CO_2-C m^{-2} day^{-1} in most of the sampling dates (Figure 3).

In 2015, soil CH_4 fluxes showed significant differences between irrigation frequencies, with greater net CH_4 uptake in L irrigation compared with H irrigation (Table 4). For the rest of measurement periods no significant differences were observed for soil CH_4 fluxes.

In 2015, soil N_2O fluxes were affected by irrigation time with the greatest N_2O emissions observed under N irrigation compared with D irrigation (Table 4, Figure 4). Furthermore, in 2016, the interaction between irrigation time, frequency and date was significant for soil N_2O fluxes.

Soil N_2O fluxes were low in most of the sampling dates, especially during the fallow period. In contrast, soil N_2O flux showed a great increment after the fertilizer was added, especially after top dressing applications of the nitrogen fertilizer (N-32 % solution). These N_2O peak events occurred 24 h and 48 h after the fertilizer applications (Figure 4). In 2015, the maximum N_2O flux, 21 mg N_2O-N m^{-2} day^{-1}, was measured after the top dressing application of the nitrogen fertilizer. In contrast, in 2016, two high emissions peak events of N_2O were observed, with maximum values of 11 and 19 mg N_2O-N m^{-2} day^{-1} for the first and the second top dressing application respectively.

Significant relationships were found between soil temperature at 5 cm depth and soil CO_2 and N_2O fluxes. Both relationships showed an exponential growth of soil CO_2 (Figure 5a) and N_2O (Figure 5b) fluxes as the soil temperature increased. Nevertheless, any of the correlations between GHG fluxes and neither soil water content nor soil NO_3^- and NH_4^+ contents were significant (data not shown).

3.3 Cumulative soil CO_2, CH_4 and N_2O emissions, grain yield and yield-scaled emissions.

Cumulative soil CO_2 emissions were affected by the interaction between irrigation time, frequency and measurement period (Table 5 and Figure 6). Cumulative soil CO_2 emissions in 2015 were higher compared with 2016 and the fallow period. The lowest cumulative CO_2 values occurred during the fallow period.

In 2015, the NL treatment resulted in lower cumulative CO_2 emissions than the DL and NH treatments. However, in 2016 and the fallow period, the irrigation treatments did not affect cumulative CO_2 emissions (Figure 6).

Cumulative soil CH_4 emissions were not affected by the period, irrigation time or frequency (Table 5). As an average of treatments and sampling dates, a net uptake of CH_4 was observed.

Cumulative soil N_2O emissions were significantly affected by the measurement period and by the irrigation time (Table 5). Regarding the measurement period, 2015 was the measurement period with the greatest cumulative N_2O emissions, 2.61 kg N_2O-N ha^{-1}, being two and eleven times higher compared with the values observed in 2016 and in the fallow period, respectively. Furthermore, N presented the highest cumulative N_2O emission with a mean value throughout the three measurement periods of 1.60 kg N_2O-N ha^{-1} that was 36% higher compared with D irrigation.

Grain yield was affected by the measurement period, irrigation time and the interaction between irrigation time and frequency (Table 4). Grain yield was higher in 2016 compared with 2015. Grain yield was higher when the irrigation water was applied at nighttime. H frequency irrigation decreased the grain yield when irrigation was applied at daytime, while irrigation frequency did not affect grain yield when irrigation was applied at nighttime. Finally, grain yield scaled N_2O emissions and N-uptake scaled N_2O emissions were only affected by the measurement period. In 2015, the scaled N_2O emissions almost doubled those measured in 2016.

4. Discussion

4.1. Sprinkler irrigation management and GHG emissions

According to the results obtained in this study, sprinkler irrigation management affected soil water content leading to a considerable impact not only on soil GHG emissions but also on maize grain yield.

The soil CO_2 fluxes measured for the entire gas sampling period were in the range of values found in the literature for sprinkler-irrigated maize systems (e.g. Alluvione et al., 2009; Ghimire et al., 2017). Irrigation time and frequency together with the sampling date affected daily CO_2 fluxes in both maize growing seasons but not during the fallow period. Soil CO_2 fluxes tended to increase in the treatments that were irrigated during D time. This trend could be related with greater WFPS observed under N compared with D, due to the lower water losses during N irrigation events (Playán et al., 2005; Cavero et al., 2008; Martínez-Cob et al., 2008). These greater WFPS values in N treatments could resulted in lower gas diffusivity conditions (Smith et al., 2003; Ball et al., 2008) because of the negative impact of WFPS on the soil diffusivity (Buckingham, 1904; Penman, 1940; Millington and Quirk, 1961) resulting in lower CO_2 fluxes under N irrigation.

Irrigation time and frequency and the measurement period had an impact on the cumulative CO_2 emissions. On average, cumulative CO_2 emissions in 2015 were 1.46 times higher than those in 2016, and 5.3 times greater than during the fallow period. It is important to know that soil CO_2 emissions measured in this study are the combination of the autotrophic (i.e. root derived) and heterotrophic (i.e. microorganism derived) respiration. Thus, the higher soil CO_2 emission obtained in both maize growing seasons compared with the fallow period were explained by the presence of the crop as well as the effect of soil temperature on the microorganism activity (Lloyd and Taylor, 1994; Fang and Moncrieff, 2001), as it was shown in the positive relationship between soil temperature and soil CO_2 fluxes. Furthermore, the higher WFPS values in 2015 could result in more optimal conditions for microorganism activity (Linn and Doran, 1984) along with the crop residues of the previous alfalfa crop, which could explain the greater cumulative CO_2 emissions measured in 2015 compared to those in 2016. This finding agrees with the results of Adviento-Borbe et al. (2010), who found higher cumulative CO_2 emission in the maize growing season of a maize-alfalfa rotation compared with a continuous maize, due to the capacity of legumes to improve the availability of carbon and nitrogen in the soil (Aulakh et al. 2001; Tejada et al. 2008).

Soil CH_4 fluxes were in the range of values observed by Sánchez-Martin et al. (2010) in Mediterranean areas. During all the experimental period, cumulative CH_4 emissions were negative, which means that soil acted as a CH_4 sink, as observed by Sanz-Cobena et al. (2014). As reported by Hütsch (2001), there are different factors controlling CH_4 oxidation by the methanotophic bacteria, like soil NO_3^- and NH_4^+ content, oxygen availability, pH, etc. In addition, Le Mer and Roger (2001) described methanogenesis as a biological process that requires strict anaerobiosis and low oxido-reduction potentials. In this study, WFPS values were far from the values needed for a strict anaerobiosis condition. Moreover, these low WFPS values could positively affect soil diffusivity resulting in a better air-filled porosity and an optimal circulation of soil gases (Ball et al, 1999; Smith et al., 2003; Ball et al. 2008), thus providing a more suitable condition for methane consumption.

Soil N_2O fluxes were similar to the fluxes found in other studies for irrigated maize (Halvorson et al., 2010; Lui et al., 2005). In both maize growing seasons, irrigation management through its effect on the WFPS had an important effect on N_2O fluxes. The WFPS is considered as a key factor on the production of N_2O in the soil (Bouwman et al., 2002; Butterbach-Bahl et al., 2013).

In 2015, irrigation time affected soil N_2O fluxes. In this growing season, N irrigation presented a mean N_2O flux value 1.65 times greater than D. The greatest N_2O flux under N was explained by the increment of 19 % in WFPS values with N irrigation compared to D irrigation. In 2016 growing season, however, it was the interaction between the irrigation treatments and the sampling date, which influenced the daily N_2O fluxes. This interaction mainly affected the N_2O fluxes just after the first top dressing application of the nitrogen fertilizer and the following month, observing the greatest N_2O peak under DL treatment.

Regarding the cumulative N_2O emissions, the values reported in this work were close to the values obtained by Álvaro-Fuentes et al. (2016) and Maris et al. (2018) for sprinkler-irrigated maize systems in the Ebro Valley (NE Spain), but lower than the values reported in the two meta-analysis published for Mediterranean conditions (Aguilera et al., 2013; Cayuela et al., 2017). These two studies reported cumulative soil N_2O emissions of 4 kg ha^{-1} for sprinkler irrigation and cumulative N_2O emissions close to 5 kg ha^{-1} for maize. However, cumulative N_2O emissions in this study were 35% (2015) and 70 % (2016) lower compared with the cumulative N_2O emissions presented in the previous meta-analysis for sprinkler irrigation under Mediterranean conditions (Aguilera et al., 2013; Cayuela et al., 2017). Differences between the two previous meta-analyses and our study could be explained by the fact that both meta-analysis used a large number of studies with different combinations of sources and rates of nitrogen fertilizer, irrigation systems, crops, etc.

Cumulative N_2O emissions measured were different in the three periods of measurement. Cumulative emissions observed in both growing seasons were 10 (2015) and 5 (2016) times higher than in the fallow period since during the fallow period no nitrogen fertilizer nor irrigation water were applied. Furthermore, cumulative N_2O

emissions in 2015 were two-fold greater than in 2016. Differences in WFPS and in the the carbon and nitrogen provided by the residues of the previous alfalfa crop could explain this difference. According to Bateman and Baggs (2005), nitrification is the predominant process contributing to N_2O emissions when WFPS values range between 35–60 % WFPS. In contrast, when WFPS values are higher than 60% denitrification mainly control the production of N_2O. In 2015, in 69% of the sampling dates WFPS values were within the optimum range for nitrification and denitrification processes while in 2016, only the 46% of the sampling dates reached these optimal conditions. Although less N fertilizer was applied in 2015, the higher production of N_2O this year was probably related with the fact that the previous crop was a legume, which usually results in an increment of the availability of nitrogen in the soil for the following crop (Ballesta and Lloveras et al., 2010, Salmerón et al., 2010; Cela et al., 2011). Therefore, the greater number of sampling dates in which nitrification and denitrification processes could occur, together with the N mineralized from the residues of the previous alfalfa could lead to more optimal conditions for the N_2O productions during the 2015 maize growing season.

4.2. Grain yield- and N uptake-scaled GHG emissions

Under this high-yielding maize system, grain yield values were similar to the values obtained by Urrego-Pereira et al. (2013a) and Robles et al. (2017) in the same location.

Irrigation time affected the maize grain yield, reporting a decrease of the 13% in D irrigation compared with N irrigation. The reduction of maize yield with daytime irrigation is explained by the lower irrigation uniformity, the reduction of net photosynthesis, the higher WDEL (i.e. wind drift and evaporation losses), and the higher accumulation of Na^+ in maize (Cavero et al., 2009; Urrego-Pereira et al., 2013a and b; Cavero et al., 2018). Besides, the decrease in maize grain yield when sprinkler irrigation frequency was increased at D irrigation was related to the higher water losses and the increased Na^+ in the maize plant (Cavero et al., 2018).

The ratio of N_2O emissions per unit of crop yield or per unit of grain N-uptake (i.e. grain yield-scaled N_2O emissions and N-uptake-scaled N_2O emissions) is a good estimator of the N_2O efficiency of a cropping system (Van Groenigen et al., 2010). N_2O emissions per unit of grain yield and per unit of grain N-uptake obtained in this study were in the range of the values reported by Venterea et al (2011) and Omonode et al (2015) for maize under different tillage and different N sources and N rates application. In our study, only 2015 showed differences in N_2O scaled emissions due to the lower grain yield in 2015 and the effect of the preceding alfalfa crop. Sprinkler irrigation time affected N_2O emissions, but when emissions were expressed on the basis of grain yield or grain N uptake, differences disappeared due to the effect of irrigation time on maize yield and, consequently, on N uptake (Pandey et al., 2000).

5. Conclusions

The results of this work showed that the sprinkler irrigation time had a greater impact on the soil GHG emissions and on the grain yields compared with the sprinkler irrigation frequency. Nighttime irrigation increased N_2O emissions and grain yields, regardless if the irrigation was applied with a high or low frequency. However, N_2O emissions did not show differences due to irrigation management when emissions were estimated based on the grain yields or based on the N uptake. Due to lack of differences found in scaled N_2O emissions and in order to optimize the grain yield and reduce water losses, sprinkler irrigation should be applied at nighttime. Finally, this work emphasize the importance of the appropriate management of the irrigation under Mediterranean conditions to increase the yields without a significant increment of the GHG.

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Figure captions.

Figure 1. Air temperature (black continuous line), precipitation (black bars) and reference evapotranspiration (ETo) (grey continuous line) during the experimental period

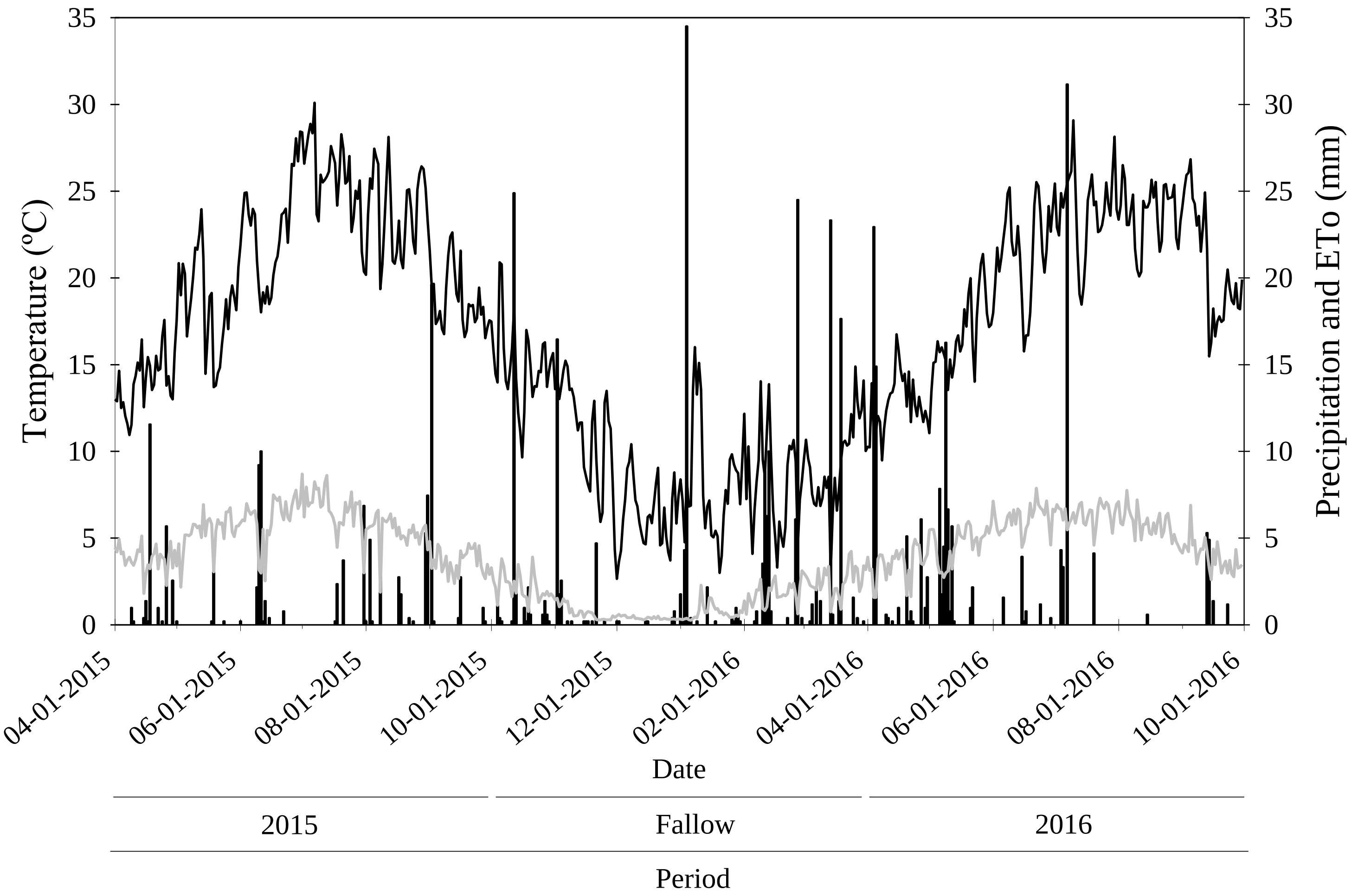
Figure 2. Soil water-filled pore space (WFPS) as affected by irrigation time and irrigation frequency (DH, daytime high frequency; DL, daytime low frequency; NH, nighttime high frequency; NL, nighttime low frequency). *Indicates significant differences between treatments for each date at $p<0.05$. Triangles indicate fertilizer applications.

Figure 3. Soil CO_2 flux as affected by irrigation time and irrigation frequency (DH, daytime high frequency; DL, daytime low frequency; NH, nighttime high frequency; NL, nighttime low frequency). *Indicates significant differences between treatments for each date at $p<0.05$. Triangles indicate fertilizer applications.

Figure 4. Soil N_2O fluxes as affected by irrigation time and irrigation frequency (DH, daytime high frequency; DL, daytime low frequency; NH, nighttime high frequency; NL, nighttime low frequency). *Indicates significant differences between treatments for each date at $p<0.05$. Triangles indicate fertilizer applications.

Figure 5. Regression analysis between soil temperature (5 cm depth) and CO_2 (a) and N_2O (b) fluxes. Each point represents the average value of all treatments for each sampling date.

Figure 6. Cumulative CO_2 emissions as affected by measurement period (2015, 2015 growing season; 2016, 2016 growing season; fallow, fallow period between growing seasons), irrigation time and irrigation frequency (DH, daytime high frequency; DL, daytime low frequency; NH, nighttime high frequency; NL, nighttime low frequency). Different letters indicate significant differences between treatments at $p<0.05$.



Temperature (ºC)
Precipitation and ETo (mm)
Date
04-01-2015
06-01-2015
08-01-2015
10-01-2015
12-01-2015
02-01-2016
04-01-2016
06-01-2016
08-01-2016
10-01-2016
2015
Fallow
2016
Period

Fig. 1

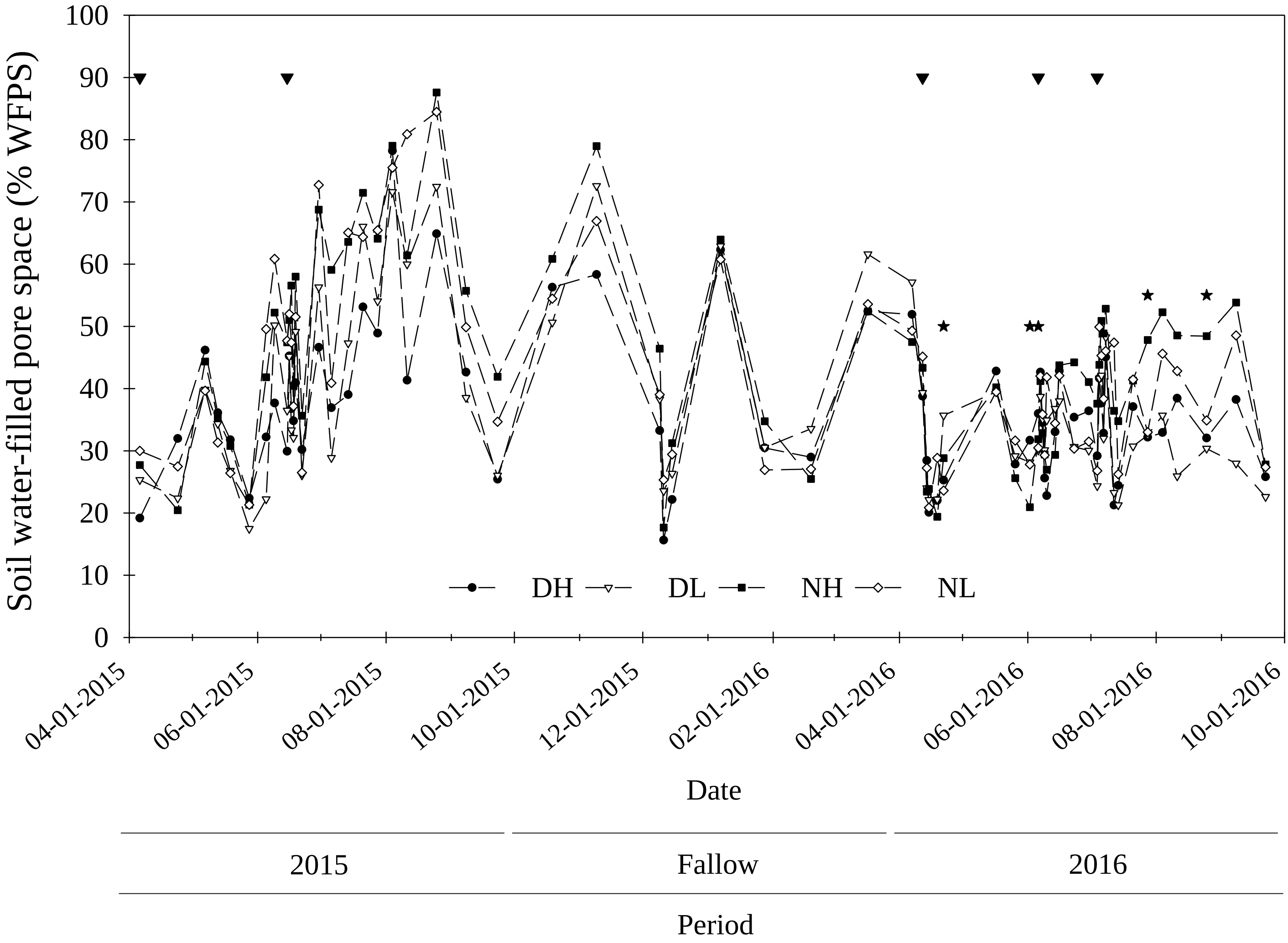

Soil water-filled pore space (% WFPS)
0
10
20
30
40
50
60
70
80
90
100
DH
DL
NH
NL
04-01-2015
06-01-2015
08-01-2015
10-01-2015
12-01-2015
02-01-2016
04-01-2016
06-01-2016
08-01-2016
10-01-2016
Date
2015
Fallow
2016
Period

Fig. 2

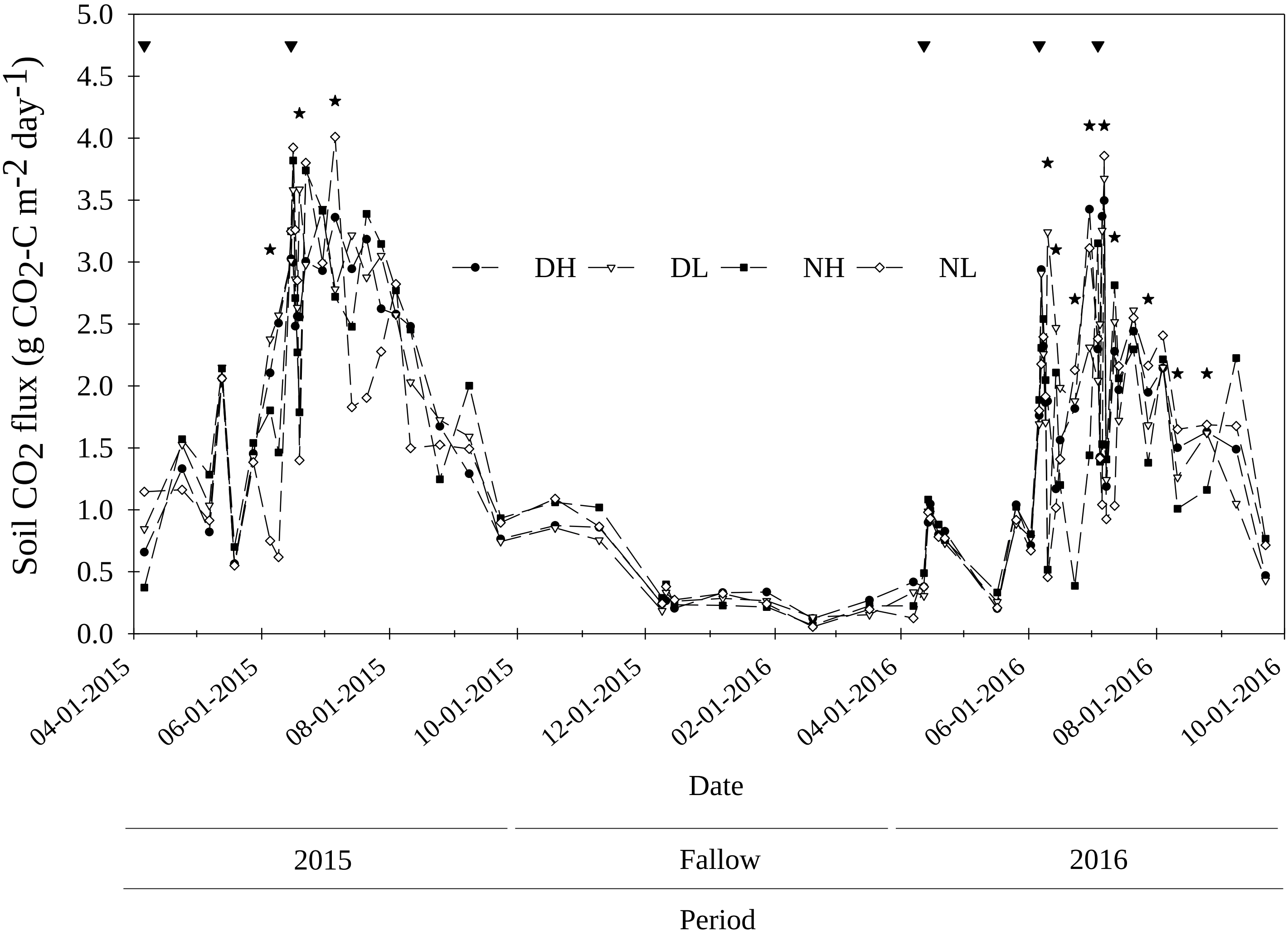
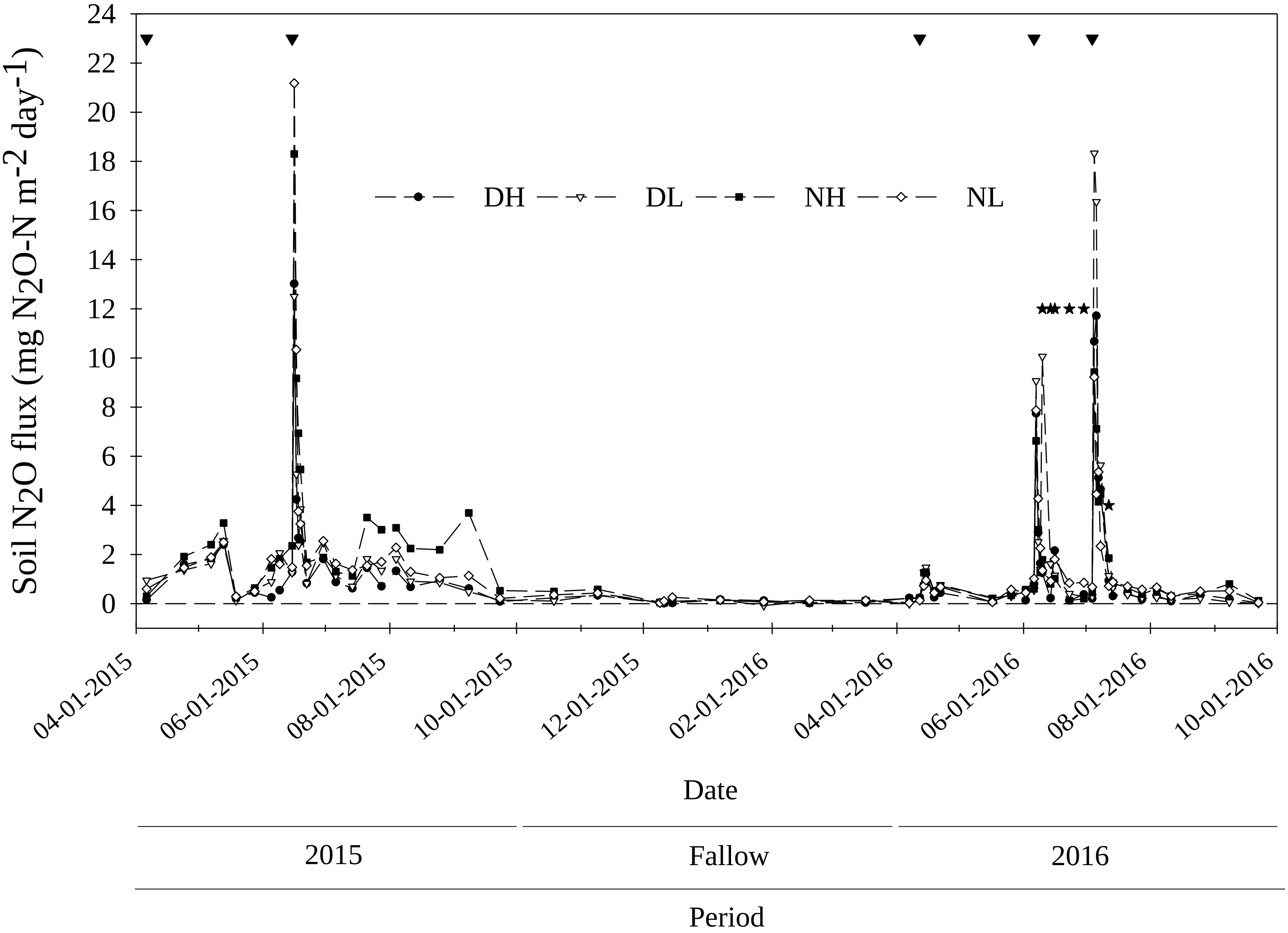

Soil CO2 flux (g CO2-C m-2 day-1)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
DH
DL
NH
NL
04-01-2015
06-01-2015
08-01-2015
10-01-2015
12-01-2015
02-01-2016
04-01-2016
06-01-2016
08-01-2016
10-01-2016
Date
2015
Fallow
2016
Period

Fig. 3



Soil N_2O flux (mg N_2O-N m^{-2} day^{-1})
24
22
20
18
16
14
12
10
8
6
4
2
0
DH
DL
NH
NL
04-01-2015
06-01-2015
08-01-2015
10-01-2015
12-01-2015
02-01-2016
04-01-2016
06-01-2016
08-01-2016
10-01-2016
Date
2015
Fallow
2016
Period

Fig. 4

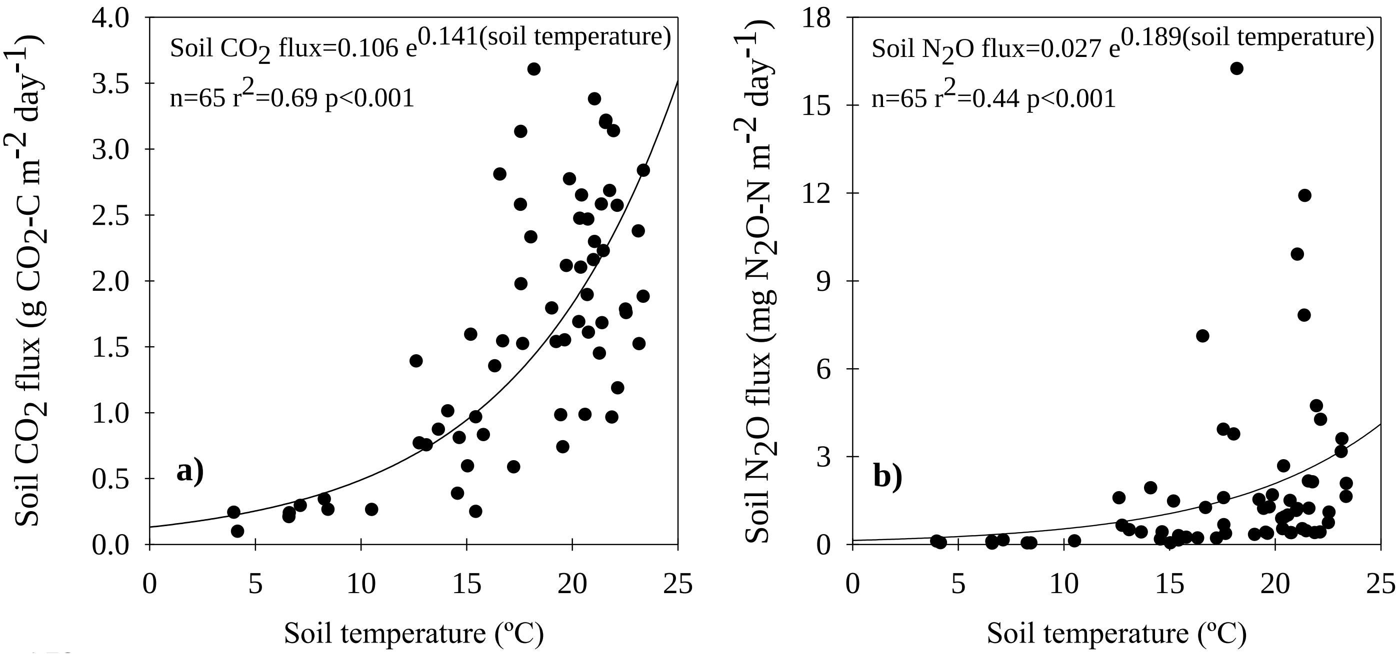

Soil CO2 flux (g CO2-C m-2 day-1)
Soil CO2 flux=0.106 e0.141(soil temperature)
n=65 r2=0.69 p<0.001
a)
Soil temperature (ºC)
Soil N2O flux (mg N2O-N m-2 day-1)
Soil N2O flux=0.027 e0.189(soil temperature)
n=65 r2=0.44 p<0.001
b)
Soil temperature (ºC)

Fig. 5

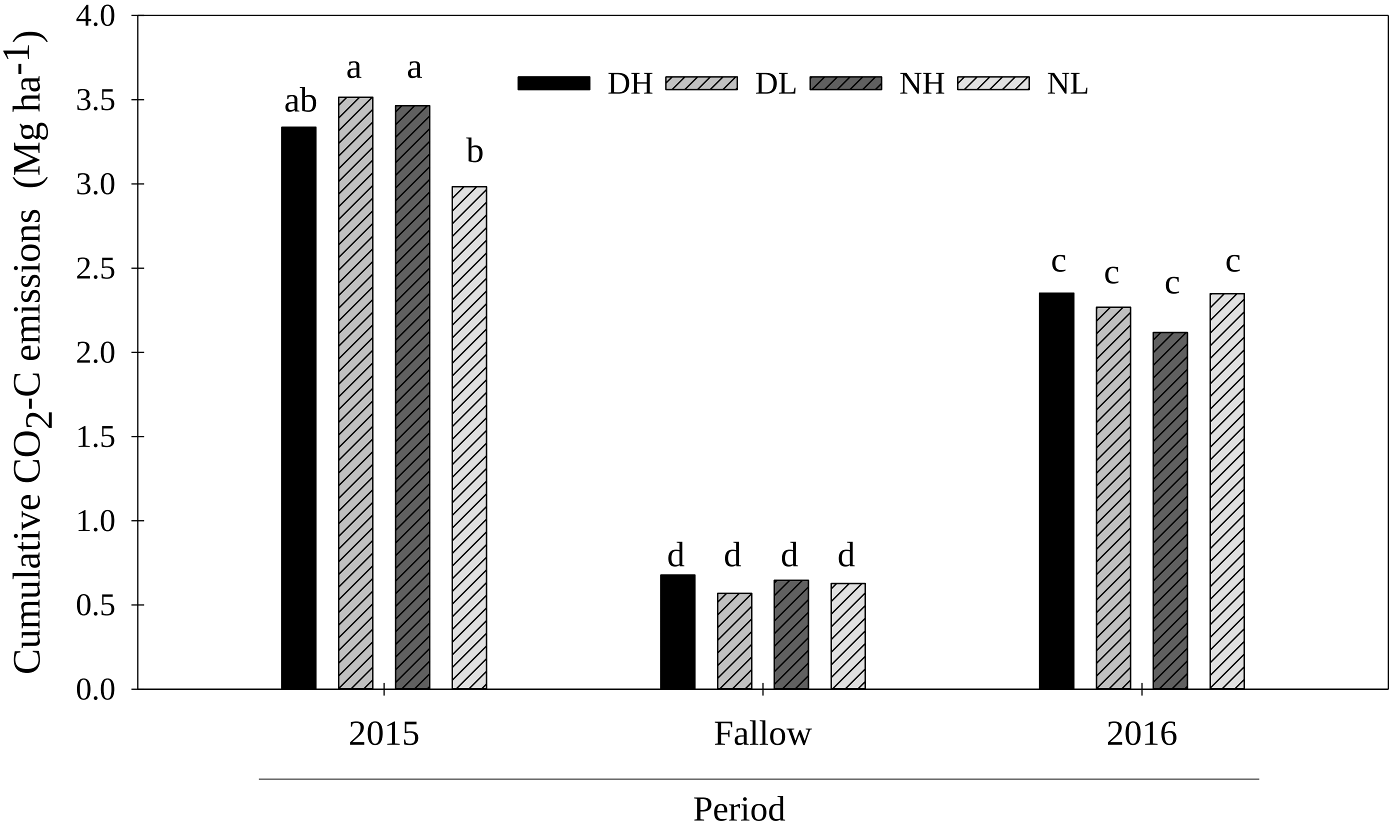

Cumulative CO2-C emissions (Mg ha-1)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
DH
DL
NH
NL
ab
a
a
b
d
d
d
d
c
c
c
c
2015
Fallow
2016
Period

Fig. 6

Table 1. Soil characteristics of the experimental field (Cavero et al., 2016).

Depth	pH	C	N	$CaCO_3$	Sand	Silt	Clay	FC[a]	WP[b]
(m)		(%)						(m^3 m^{-3})	
0.0−0.3	8.2	1.12	0.14	35	19.6	50.2	30.2	0.351	0.189
0.3−0.6	8.3	0.77	0.11	35	14.9	47.5	37.6	0.381	0.227
0.6−0.9	8.3	0.54	0.10	32	7.7	47.5	44.8	0.364	0.207
0.9−1.2	8.2	0.43	0.08	31	11.9	47.1	41.0	0.359	0.187
1.2−1.6	8.3	0.43	0.07	33	20.3	49.2	30.5	0.344	0.187

[a] FC, field capacity (-0.033 MPa). [b] WP, permanent wilting point (-1.5 MPa).

Table 2. Field operation scheduling.

Field operation	2015	2016
Tillage operation		
Subsoiler and disk harrow	10/12/2015	17/01/2016
Rotary tiller	13/04/2015	13/04/2016
Planting operation		
Sowing	14/04/2015	13/04/2016
Fertilization operation		
Preplanting application	09/04/2015	11/04/2016
Top dressing application	15/06/2015	06/06/2016; 04/07/2016
Harvest operation		
Harvest	30/09/2015	06/10/2016

Table 3. Crop evapotranspiration (ETc), precipitation (P), crop irrigation requirement (CIR) and irrigation water applied to maize in the 2015 and 2016 growing seasons.

Growing season	ETc (mm)	P (mm)	CIR (mm)	Irrigation (mm)
2015	741	115	606	614
2016	772	130	609	601

Table 4 Analysis of variance (ANOVA) of soil water-filled pore space (WPFS), nitrate and ammonium content in soil (0–5 cm) and fluxes of CO_2, CH_4 and N_2O by measurement period as affected by irrigation time (D, daytime; N, nighttime), irrigation frequency (H, high; L, low) and date of sampling and their interactions.

Effect and levels[†]	WFPS (%)			Soil nitrate content (kg NO_3^--N ha^{-1})			Soil ammonium content (kg NH_4^+-N ha^{-1})			Gas fluxes								
										CO_2 (g CO_2-C m^{-2} day^{-1})			CH_4 (mg CH_4-C m^{-2} day^{-1})			N_2O (mg N_2O-N m^{-2} day^{-1})		
	2015	Fallow	2016	2015	Fallow	2016	2015	Fallow	2016	2015	Fallow	2016	2015	Fallow	2016	2015	Fallow	2016
D	40.65 b	43.44	32.23 b	36.56	28.95	71.66	3.56	0.62	5.31	2.27 a	0.38	1.72 a	-0.18	-0.14	-0.07	1.89 b	0.10	2.20
N	50.40 a	44.60	36.90 a	40.20	24.26	62.59	2.60	0.65	6.40	2.17 b	0.41	1.51 b	-0.12	-0.01	-0.14	3.12 a	0.17	1.68
H	45.72	43.55	35.26 a	40.42	26.80	72.00	3.01	0.62	5.71	2.24	0.40	1.58	-0.09 a	-0.09	-0.11	2.56	0.14	1.74
L	45.33	44.50	33.86 b	36.28	26.41	62.25	3.21	0.65	6.00	2.20	0.38	1.64	-0.21 b	-0.06	-0.09	2.43	0.13	2.13
DH	40.27 c	41.18	32.74	37.73	29.14	78.07	3.54	0.61	5.29	2.20 ab	0.40	1.69	-0.12	-0.17	-0.07	1.75	0.11	1.81
DL	41.04 c	45.71	31.72	35.38	28.77	65.24	3.59	0.63	5.33	2.34 a	0.36	1.74	-0.24	-0.10	-0.07	2.03	0.09	2.58
NH	51.14 a	45.92	37.79	43.09	24.47	65.93	2.49	0.63	6.13	2.27 ab	0.40	1.48	-0.06	0.00	-0.16	3.37	0.17	1.67
NL	49.65 b	43.28	36.01	37.19	24.05	59.26	2.82	0.66	6.68	2.06 b	0.41	1.54	-0.19	-0.01	-0.11	2.85	0.17	1.68
ANOVA																		
Irrigation Time	*<0.001*	NS	*<0.001*	NS	NS	NS	NS	NS	NS	*<0.05*	NS	*<0.01*	NS	NS	NS	*<0.05*	NS	NS
Irrigation Frequency	NS*	NS	*<0.01*	NS	NS	NS	NS	NS	NS	NS	NS	NS	*<0.05*	NS	NS	NS	NS	NS
Date	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	NS	NS	NS	*<0.001*	*<0.001*	*<0.001*
Time x Frequency	*<0.05*	NS	NS	NS	NS	NS	NS	NS	NS	*<0.05*	NS	NS	NS	NS	NS	NS	NS	NS
Time x Date	*<0.001*	NS	*<0.001*	NS	NS	NS	*<0.001*	NS	NS	*<0.001*	*<0.01*	*<0.001*	NS	NS	NS	NS	NS	*<0.001*
Frequency x Date	*<0.001*	NS	*<0.001*	NS	NS	NS	NS	*<0.001*	NS	NS	NS	*<0.001*	NS	NS	NS	NS	NS	*<0.001*
Time x Frequency x Date	NS	NS	*<0.01*	NS	NS	NS	NS	NS	NS	*<0.05*	NS	*<0.001*	NS	NS	NS	NS	NS	*<0.001*

[†]For each effect, period and variable values followed by different letters are significantly different according to a Tukey test at P = 0.05 level.

* NS, No significant

Table 5. Analysis of variance (ANOVA) of cumulative CO_2, CH_4 and N_2O emissions, grain yield and the ratios between N_2O emission and grain yield and grain N uptake, as affected by the measurement period (2015, 2015 growing season; 2016, 2016 growing season; fallow, fallow period between growing seasons), irrigation time (D, daytime; N, nighttime), irrigation frequency (H, high; L, low) and their interactions.

Effect and levels†	Cumulative emissions			Grain yield	N_2O-N emission ratio to	
	CO_2 (Mg CO_2-C ha^{-1})	CH_4 (kg CH_4-C ha^{-1})	N_2O (kg N_2O-N ha^{-1})	(Mg ha^{-1})	Grain yield (g Mg^{-1})	N uptake (g kg^{-1})
2015	3.32 a	-0.23	2.61 a	14.09 b	182.4 a	10.39 a
Fallow	0.63 c	-0.13	0.25 c			
2016	2.27 b	-0.21	1.29 b	15.78 a	82.5 b	5.42 b
D	2.12	-0.23	1.17 b	14.00 b	120.2	7.48
N	2.03	-0.15	1.60 a	15.87 a	144.7	8.15
H	2.09	-0.17	1.41	14.84	135.5	7.52
L	2.05	-0.21	1.36	15.03	129.4	8.06
DH	2.12	-0.23	1.04	13.53 c	110.2	6.72
DL	2.11	-0.23	1.3	14.47 b	130.1	8.24
NH	2.08	-0.11	1.78	16.15 a	160.8	8.49
NL	1.99	-0.19	1.41	15.59 a	128.6	7.87
ANOVA						
Period	<0.001	NS	<0.001	<0.001	<0.001	<0.001
Irrigation Time	NS*	NS	<0.001	<0.001	NS	NS
Irrigation Frequency	NS	NS	NS	NS	NS	NS
Time x Frequency	NS	NS	NS	<0.05	NS	NS
Period x Irrigation Time	NS	NS	NS	NS	NS	NS
Irrigation Frequency	NS	NS	NS	NS	NS	NS
Period x Time x Frequency	<0.01	NS	NS	NS	NS	NS

†For each effect and variable the numbers with different letters are significantly different according to a Tukey test at P = 0.05 level.

* NS, No significant